

## **PROCESS DEVICE WITH VIBRATION BASED DIAGNOSTICS**

### BACKGROUND OF THE INVENTION

The present invention relates to diagnostics of equipment used with industrial processes. More specifically, the invention relates to process devices which perform diagnostics.

Process devices are used in industrial process control systems to control, measure or monitor a process. A control device is a process device which is used to control the process and includes pumps, valves, actuators, solenoids, motors, mixers, agitators, breaker, crusher, roller, mill, ball mill, kneader, blender, filter, cyclone, centrifuge, tower, dryer, conveyor, separator, elevator, hoist, heater, cooler or others. A valve controller includes a valve actuator coupled to a valve used to control flow of process fluid. A pump controller includes a motor controller or actuator coupled to a pump. Other process devices include transmitters which may measure physical parameters such as pressure, temperature, flow, etc. Diagnostics of process devices can be used to identify a failed process device or predict an impending failure in the device or another process component.

Vibration of process equipment such as process piping is disruptive to industrial processes and can result in damage to the piping, instrumentation, and other components of the industrial plant. For example, during normal

operation of the process, vibration arises through various sources. The vibration is transmitted to the components which are used in the process. Over extended time, these vibrations can cause degradation 5 in the performance of the components and eventual failure of the components.

Sensing vibrations is a known method used to diagnose process devices. A vibration sensor such as an accelerometer placed directly on a process 10 device can be used to sense vibration noise signals generated by the device. Vibrations are isolated and evaluated by identifying those which exceed an amplitude threshold or which have an abnormal frequency which are indicative of an actual or 15 impending failure or reduction of performance. For example, sensors are placed on pump or motor housings, discharge valves, or flanges associated with the process device. Another known diagnostic method is a manual inspection in which an operator 20 listens for abnormal sounds from the control device.

Detecting harmful vibrations can allow damaged process equipment to be replaced prior to its ultimate failure. Similarly, the vibrations can be used to detect aberrations in operation of equipment 25 or to compensate for degradation in components of the equipment. There is an ongoing need for improved diagnostic technology in industrial process control and monitoring for detecting failed components and components which have been degraded or are in the

process of failing. One such technique is shown in U.S. Patent No. 6,601,005, issued July 29, 2003 and entitled PROCESS DEVICE DIAGNOSTICS USING PROCESS VARIABLE SENSOR SIGNAL which is incorporated herein 5 by reference.

SUMMARY OF THE INVENTION

A process device for use in an industrial process control or monitoring system is configured to couple to a process. The apparatus includes a 10 vibration sensor configured to sense vibrations. These vibrations may be received through a process coupling, mounting arrangement or wiring system and provide a sensed vibration signal. Diagnostic circuitry receives the sensed vibration signal and 15 responsively provides diagnostic output related to a condition of the process or process component. A method of diagnostic process operation based upon sensed vibrations is also provided.

BRIEF DESCRIPTION OF THE DRAWINGS

20 Figure 1 is a diagram of an industrial process including a process transmitter coupled to process piping.

Figure 2 is a block diagram of circuitry and components in the process transmitter of Figure 25 1.

Figure 3 is a simplified block diagram of a process device for use in implementing the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a diagnostic technique for detecting a failure or predicting a failure or reduction in performance of a process device or a process component prior to the occurrence 5 of the failure or reduced performance. With the present invention, vibrations in the process and/or process device are monitored. Vibrations are detected and used to predict a failure, an impending failure, or reduced performance of the process device or 10 process component.

Figure 1 is a diagram of process control system 10 which includes a transmitter 12 connected to process pipe 16. As discussed below, transmitter 12 is one type of process device and the present 15 invention is applicable to any process device. Transmitter 12 is coupled to a two-wire process control loop 18 which operates in accordance with the Fieldbus, Profibus or HART® standard. However, the invention is not limited to these standards or a two- 20 wire configuration. Two-wire process control loop 18 runs between transmitter 12 and the control room 20. In an embodiment in which loop 18 operates in accordance with the HART® protocol loop 18 can carry a current I which is representative of a sensed 25 process variable. Additionally, the HART® protocol allows a digital signal to be superimposed on the current through loop 18 such that digital information can be sent to or received from transmitter 12. When operating in accordance with the Fieldbus standard,

loop 18 carries a digital signal and can be coupled to multiple field devices such as other transmitters.

The present invention is applicable to any process device which is used in a process control 5 environment. In general, process devices, such as transmitter 12 shown in FIG. 1 are used to measure, monitor or control process variables.

Process variables are typically the primary variables which are being controlled in a process. As 10 used herein, process variable means any variable which describes the condition of the process such as, for example, pressure, flow, temperature, product level, pH, turbidity, vibration, position, motor current, any other characteristic of the process, 15 etc. Control signal means any signal (other than a process variable) which is used to control the process. For example, control signal means a desired process variable value (i.e. a setpoint) such as a desired temperature, pressure, flow, product level, 20 pH or turbidity, etc., which is adjusted by a controller or used to control the process. Additionally, a control signal means, calibration values, alarms, alarm conditions, the signal which is provided to a control element such as a valve 25 position signal which is provided to a valve actuator, an energy level which is provided to a heating element, a solenoid on/off signal, etc., or any other signal which relates to control of the process. A diagnostic signal as used herein includes

information related to operation of devices and elements in the process control loop, but does not include process variables or control signals. For example, diagnostic signals include valve stem 5 position, applied torque or force, actuator pressure, pressure of a pressurized gas used to actuate a valve, electrical voltage, current, power, resistance, capacitance, inductance, device temperature, stiction, friction, full on and off 10 positions, travel, frequency, amplitude, spectrum and spectral components, stiffness, electric or magnetic field strength, duration, intensity, motion, electric motor back emf, motor current, loop related parameters (such as control loop resistance, voltage, 15 or current), or any other parameter which may be detected or measured in the system. Furthermore, process signal means any signal which is related to the process or element in the process such as, for example, a process variable, a control signal or a 20 diagnostic signal. Process devices include any device which forms part of or couples to a process control loop and is used in the control or monitoring of a process.

As discussed above, FIG. 1 is a diagram 25 showing an example of a process control system 10 which includes process piping 16 which carries a process fluid and two wire process control loop 18 carrying loop current I. A transmitter 12, controller 22, which couples to a final control

element in the loop such as an actuator, valve, a pump, motor or solenoid, communicator 26, and control room 20 are all part of process control loop 18. It is understood that loop 18 is shown in one configuration and any appropriate process control loop may be used such as a 4-20 mA loop, 2, 3 or 4 wire loop, multi-drop loop and a loop operating in accordance with the HART®, Fieldbus or other digital or analog communication protocol. In operation, transmitter 12 senses a process variable such as flow using sensor 21 and transmits the sensed process variable over loop 18. The process variable may be received by controller/valve actuator 22, communicator 26 and/or control room equipment 20. Controller 22 is shown coupled to valve 24 and is capable of controlling the process by adjusting valve 24 thereby changing the flow in pipe 16. Controller 22 receives a control input over loop 18 from, for example, control room 20, transmitter 12 or communicator 26 and responsively adjusts valve 24. In another embodiment, controller 22 internally generates the control signal based upon process signals received over loop 18. Communicator 26 may be the portable communicator shown in Figure 1 or may be a permanently mounted process unit which monitors the process and performs computations. Process devices include, for example, transmitter 12 (such as a 3051S transmitter available from Rosemount Inc. of Chanhassen, Minnesota), controller 22, communicator

26 and control room 20 shown in Figure 1. A diagnostic unit 27 is also illustrated in Figure 1 and can include a sensor, such as the vibration sensors discussed herein, which is not separately  
5 used to sense a process variable. Another type of process device is a PC, programmable logic unit (PLC) or other computer coupled to the loop using appropriate I/O circuitry to allow monitoring, managing, and/or transmitting on the loop.

10 Any of the process devices 12, 20, 22, 26 or 27 shown in FIG. 1 may include a diagnostic capability in accordance with the present invention.

Any of the process devices shown in Figure 1 which physically couples to the industrial process,  
15 for example, to process piping 16 can include a sensor to sense vibration in accordance with the invention. During process operation, vibrations occur and are transmitted to process components. A generic process component 29 is illustrated in Figure 1 and  
20 can comprise any physical item which receives or generates vibrations from operation of the process. Component 29 can comprise components within the process device which perform the diagnostics. The vibrations can be from various sources such as  
25 motors, cavitation or fluid movement, actuators, etc. The vibrations are physically carried along the process components which are illustrated by arrow 30. These vibrations can cause the degradation and ultimate failure of process component 29. Process

component 29 can be any component which is coupled to industrial process 10. Example process components include process piping, valves, pumps, sensors, transmitters, electrical equipment, mechanical equipment, control elements, conduits, tanks, actuators, agitators, or other components or devices.

In accordance with one embodiment of the present invention, a process device, such as transmitter 12 includes a vibration sensor configured to sense vibrations occurring in the industrial process. The vibration sensor can be any type of vibration sensor such as an accelerometer. Diagnostic circuitry in transmitter 12 or at a remote location monitors the sensed vibrations and is capable of diagnosing a failure or an impending failure, or degradation of performance of process component 29. The component 29 can, in some embodiments, comprise a component of the process device which performs the diagnostics. In other embodiments, the component 29 is physically separated from the device which performs the diagnostics. An output can be provided by transmitter 12, for example to control room 20 over two-wire process control loop 18, which provides an indication of the failure of impending failure of process component 29. Using this information, an operator can repair or replace a failed component 29, or repair or replace a component 29 prior to its ultimate failure. This allows any maintenance of the process 10 to occur at a scheduled time. This can be

particularly advantageous if the repair or replacement of the component 29 requires the process 10 to be shut down. Further, some components can fail either catastrophically or in a manner which causes 5 other components to be damaged, or cause the release of unsafe product to the environment. By providing an indication that the component 29 may fail in the near future, or predicting a time of ultimate failure, the component 29 can be repaired or replaced prior to 10 that ultimate failure.

Figure 2 is a diagram showing process transmitter 12 coupled to process piping 16. Vibrations 70 are shown traveling through the industrial process. For example, the vibration 70 may 15 be carried by process piping 16, process fluid within piping 16, or other physical couplings to transmitter 12.

Transmitter 12 includes a process variable sensor 72. Process variable sensor 72 can be 20 configured to sense any type of process variable such as flow, pressure, temperature, or others. Process variable sensor 72 couples to measurement circuitry 74 which provides a process variable signal to I/O circuitry 76. I/O circuitry 76 is configured to 25 transmit information related to the sensed process variable over two-wire process control loop 18. In some embodiments, I/O circuitry 76 can also receive power through process control loop 18 which is used

to completely power the circuitry and components of transmitter 12.

A vibration sensor 80 in transmitter 12 is configured to sense vibrations 70 and provide a 5 vibration sensor signal to diagnostic circuitry 82. Diagnostic circuitry 82 monitors the vibrations 70 sensed by vibration sensor 80 and provides an output via I/O circuitry 76 which provides an indication of a failure or impending failure of a process component  
10 29.

The vibrations 70 in process piping 16 and process equipment are disruptive to the industrial process 10 and can result in damage to the process piping 16, instrumentation, and other plant 15 components. Process transmitter 12 provides a built-in capability for monitoring the vibrations and detecting and predicting potential damage. By detecting harmful vibrations, transmitter 12 can prevent the need to replace damaged process 20 instruments or other equipment. Plant integrity and safety can also be maintained by preventing process leakage due to broken piping or damage to other equipment that provides containment of the process.

In some embodiments, the vibration 25 diagnostics of the present invention can avoid or reduce plant downtime by predicting the impending loss of a measurement instrument or a control instrument while there is still time to replace or repair the device. Vibration information can also be

provided to other devices. Data compression algorithms can be used for such transmissions. A diagnostic indication can be provided on two-wire process control loop 18. For example, a HART status or other alert can be transmitted over loop 18. Such an alert can be provided to the control room 20 when the sensed vibration exceeds a predefined threshold amplitude. The vibration diagnostic alert can be triggered if the instantaneous vibration exceeds a threshold level or, for example, if the cumulative vibration have exceeded a threshold. The accumulation can be over the sensor lifetime, partial lifetime (windowed), or an accumulation of peaks or other vibration signatures. Trends or specific vibration signatures in the vibrations can also be used for diagnostics. Because the vibration diagnostics of the present invention can be integrated with a process device, additional diagnostic devices are not required. The configuration of the vibration based diagnostics can simply be integrated with existing process information systems used in the industrial processes.

The vibration sensor 80 can be any type of vibration sensor. Many vibration sensors operate along a single axis and are capable of only sensing vibrations along that axis. However, in one embodiment additional sensors or multi-axis sensors are used to sense vibrations along more than one axis or to profile vibration at various locations in the

process device. The additional sensed vibrations can be used by the diagnostic circuitry 82 to provide further diagnostics. Additionally, vibration sensors 80 can be placed in more than one location in the 5 process transmitter 12. These additional sensors can also be used to provide additional vibration based process diagnostics. The scope of the diagnostics can be expanded by comparing or analyzing vibration measurements from more than one process device 10 located in the process system. The additional measurements can be used to provide information related to the overall health of the process or plant. Vibration measurements made near the connection of a process device to the process can be 15 used to detect specific process disruptions such as air hammer from abrupt valve closure, cavitation, aggressive chemical reactions or other process disturbances as well as actual or impending failure of pumps, rotating equipment or similar types of 20 failures.

Vibration of process piping is also disruptive to the process and may degrade the accuracy of flow measurements such as those provided by vortex flowmeters or differential pressure based 25 flowmeters that require an optimized profile. Detection of disruptive vibration can subsequently be used in the flow control algorithm, for example through curve fitting or other techniques to adjust the flow rate to settings that minimize or eliminate

these disruptions to the process and improve flow measurements. The detected vibration 70 can be used to compensate, or "trim", flow or other process variable measurements while the process is being 5 disrupted.

Although the I/O circuitry 76, measurement circuitry 74 and diagnostic circuitry 82 are shown as separate components in Figure 2, these circuit blocks can be implemented in shared circuitry and/or 10 software. For example, many of these functions can be implemented in a digital processor. In addition to comparing sensed vibrations, or cumulative sensed vibrations, to a fixed threshold, other diagnostic techniques can be employed by diagnostic circuitry 15 82. For example, an expert system can be implemented using if/then rules. Diagnostics can be based upon the frequency spectrum of sensed vibrations. Complex processing can be employed such as neural networks, fuzzy logic, etc.

FIG. 3 is a block diagram of a process device 240 forming part of loop 18. Device 240 is shown generically and may comprise any process device used to implement the vibration diagnostics such as transmitter 12, controller 22, communicator 26, unit 25 27 or control room equipment 20 shown in FIG. 1. Control room equipment 20 may comprise, for example, a DCS system implemented with a PLC and controller 22 may also comprise a "smart" motor and pump. Process device 240 includes I/O circuitry 242 coupled to loop

18 at terminals 244. I/O circuitry has preselected input and output impedance known in the art to facilitate appropriate communication from and to device 240. Device 240 includes microprocessor 246,  
5 coupled to I/O circuitry 242, memory 248 coupled to microprocessor 246 and clock 250 coupled to microprocessor 246. Microprocessor 246 receives a process signal input 252. Process signal input block 252 is intended to signify input of any process  
10 signal, and as explained above, the process signal input may be a process variable, or a control signal and may be received from loop 18 using I/O circuitry 242 or may be generated internally within process device 240. Process device 240 is shown with a sensor  
15 input channel 254 and a control channel 256. Typically, a transmitter such as transmitter 12 will exclusively include sensor input channel 254 while a controller such as controller 22 will exclusively include a control channel 256. Other devices on loop  
20 18 such as communicator 26 and control room equipment  
20 may not include channels 254 and 256. It is understood that device 240 may contain a plurality of channels to monitor a plurality of process variables and/or control a plurality of control elements as  
25 appropriate.

Sensor input channel 254 includes sensor 21, sensing a process variable and providing a sensor output to amplifier 258 which has an output which is digitized by analog to digital converter 260. Channel

254 is typically used in transmitters such as transmitter 12. Compensation circuitry 262 compensates the digitized signal and provides a digitized process variable signal to microprocessor 246. In one 5 embodiment, channel 254 comprises a diagnostic channel which receives a diagnostic signal.

When process device 240 operates as a controller such as controller 22, device 240 includes control channel 256 having control element 24 such as a 10 valve, for example. Control element 24 is coupled to microprocessor 246 through digital to analog converter 264, amplifier 266 and actuator 268. Digital to analog converter 264 digitizes a command output from microprocessor 246 which is amplified by amplifier 266. 15 Actuator 268 controls the control element 24 based upon the output from amplifier 266. In one embodiment, actuator 268 is coupled directly to loop 18 and controls a source of pressurized gas (not shown) to position control element 24 in response to the current 20 I flowing through loop 18. In one embodiment, controller 22 includes control channel 256 to control a control element and also includes sensor input channel 254 which provides a diagnostic signal such as valve stem position, force, torque, actuator pressure, 25 pressure of a source of pressurized air, etc.

In one embodiment, I/O circuitry 242 provides a power output used to completely power other circuitry in process device 240 using power received from loop 18. Typically, field devices such as

transmitter 12, or controller 22 are powered from loop 18 while communicator 26 or control room 20 has a separate power source. As described above, process signal input 252 provides a process signal to 5 microprocessor 246. The process signal may be a process variable from sensor 21, the control output provided to control element 24, a diagnostic signal sensed by sensor 80, or a control signal, process variable or diagnostic signal received over loop 18, or 10 a process signal received or generated by some other means such as another I/O channel.

A user I/O circuit 276 is also connected to microprocessor 246 and provides communication between device 240 and a user. Typically, user I/O circuit 15 276 includes a display and audio for output and a keypad for input. Typically, communicator 26 and control room 20 includes I/O circuit 276 which allows a user to monitor and input process signals such as process variables, control signals (setpoints, 20 calibration values, alarms, alarm conditions, etc.). A user may also use circuit 276 in communicator 26 or control room 20 to send and receive such process signals to transmitter 12 and controller 22 over loop 18. Further, such circuitry could be directly 25 implemented in transmitter 12, controller 22 or any other process device 240.

FIG. 3 also illustrates vibration sensor 80 which can be an individual sensor, or it can be formed from multiple sensors or components. In one

embodiment, sensor 80 couples to microprocessor 246 for example through an analog to digital converter 290 and an amplifier 292. Microprocessor 246 can monitor the sensed vibrations and provide an 5 indication of a failure or impending failure of a process component. For example, the microprocessor can compare the sensed vibration to a baseline value or a nominal value. This information can be stored in memory 248. The baseline and nominal values can 10 change based upon the mode of operation of the process, or other factors. The baseline can be a particular frequency spectrum or signature and can be based upon observed history of process operation. Further, the diagnostics performed by microprocessor 15 246 can be based upon trends in the sensed vibrations. For example, an increase, either gradual or suddenly over time, or periodic spikes or other anomalies in the sensed vibrations, can be an indication of a failure or an impending failure of a 20 process component. Similarly, if the sensed vibrations suddenly spike, the microprocessor 246 can provide a diagnostic output indicating that a process component 29 may fail or has failed. These values, trends, or training profiles can also be stored in 25 memory 248. The diagnostics can be based upon a simple comparison, or more complex mathematical techniques such as observing averages or rolling averages of measurements, fuzzy logic techniques, neural network techniques, or expert system

techniques based upon a series of rules and/or threshold comparison. In various embodiments, the ability of the present invention to provide predictive diagnostics can be advantageous because it  
5 provides time for service personnel to service the process component prior to its ultimate failure.

The diagnostic output of the present invention can be used to provide an output signal, provide a visual indication to an operator or provide  
10 a communication signal for transmission to a control room or other diagnostic annunciation.

As discussed above, the diagnostics can be based upon various techniques which employ the sensed vibration. For example, the diagnostics can utilize  
15 vibration trends over a period of time. This information can be used to correlate with wear of bearings or pump components. It can also be used to provide an accumulative measure of exposure of process components to vibration and can be used to  
20 predict the process piping or mechanical connections, such as mounting hardware or brackets are subject to imminent failure. Additionally, the diagnostics circuitry can be used to correlate vibration signals with various steps or occurrences which occur during  
25 operation of the industrial process. For example, an aggressive chemical reaction may have a particular vibration signature. In some embodiments, a simple relative measure of vibration, for example trending better, trending worse or staying constant, may be

sufficient if calibration or characterization of the vibration sensor is performed. An absolute measure of vibration can also be utilized to perform the diagnostics.

5               The vibration sensor 80 can be any appropriate vibration sensor. One known vibration detection and measurement sensor is an accelerometer. There are a number of different accelerometer technologies which are currently employed including  
10              capacitive, electrodynamic, piezoelectric, and others. The accelerometer produces an output signal that is related to the sensed vibration. The output signal can have a linear or other relationship to the strength of the vibration or the frequency of the  
15              vibration. Another example diagnostics sensor can be embodied in a MEMS configuration in which a cantilever is utilized to sense vibrations.

Piezoelectric accelerometers are fairly rugged and have a wide signal bandwidth, in the order  
20              of tens of kilohertz, covering much of the audio range. One example sensor is available from PCB Piezoelectronics and identified as the IMI Sensor Series 660, which is a family of low cost embeddable accelerometers. Various configurations are available  
25              including two wire with and without signal processing and three wire low power. For example, the low power configuration operates over an extended temperature range and can be mounted directly to processes which undergo a wide temperature variation. An excitation

voltage is applied, for example between 3 and 5 volts DC and the current throughout the sensor is on the order of 750  $\mu$ A.

Another example accelerometer is identified  
5 as the MMA series available from Motorola. These accelerometers include various options such as surface mount integrated circuit packages, temperature compensation, integral signal conditioning and filtering, self testing and fault  
10 latch capabilities. These accelerometers use a capacitive sensing technique that can be modeled as two stationary plates with a movable plate placed therebetween. The center plate is deflected from its rest position when the system is subject to  
15 acceleration.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without  
20 departing from the spirit and scope of the invention. The process coupling can be any type of coupling which is capable of transferring vibrations to the vibration sensor. The process coupling includes couplings which directly mount the vibration sensor  
25 to the process. The vibrations can be received through a process connection, mounting arrangement, wiring system, etc. In some embodiments, the invention can be embodied in any type of process device. In one embodiment, by integrating vibration

diagnostics with a process device, additional diagnostic devices are not required. The process device can perform diagnostics on itself, in other words, the component 29 can be a component of the  
5 device which receives the vibrations and/or performs the diagnostics.